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DESIGN AND TEST RESULTS OF THE 3.9 GHz CAVITY FOR LCLS-II *

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Abstract

The LCLS-II project uses sixteen 3.9 GHz superconducting cavities to linearize energy distribution before the bunch compressor. To meet LCLS-II requirements original FNAL design used in FLASH and XFEL was significantly modified to improve performance and provide reliable operation up to 16 MV/m in cw regime [1-3]. Four prototype cavities were built and tested at vertical cryostat. After dressing, one cavity was assembled and tested at horizontal cryostat as part of design verification program. All auxiliaries (magnetic shielding, power and HOM couplers, tuner) were also re-designed and tested with this cavity. In this paper we will discuss cavity and coupler design and test results.

INTRODUCTION

For the LCLS-II linac Fermilab is responsible for designing, prototyping, building and testing three 3.9 GHz cryomodules (one spare), each with eight cavities and one Beam Position Monitor (BPM). Many components of the system were modified or re-designed from the European XFEL to meet LCLS-II requirements and minimize risks. Prototypes of all components were built and tested. The design verification program is focused on demonstration of system performance in integrated tests of a single dressed cavity in a horizontal cryostat (HTS) in an environment close to that of the actual module. Both vertical tests and horizontal tests have shown performances close to or exceeding LCLS-II requirements [1]. Based on these results, the design was finalized production procurement of the major components of the 3.9 GHz system has started. As a next step we tested the first items: production cavity and coupler in HTS for final performance.

CAVITY DESIGN

The 3.9 GHz cavity design was presented previously [2].

Cavity Processing

Four prototype cavities were received from the manufacturer after completion of the mechanical fabrication; chemical treatment was done at Fermilab. The baseline surface treatment for the cavities is buffered chemical polishing (BCP) with bulk surface removal of ~110 µm, followed by hydrogen degassing at 800 C. RF inspection and tuning and a final BCP of 20 µm followed. Part of this design verification program was to test the additional benefit of 120 °C 48 hour baking.

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Cavity Tuning

Prior of welding into the helium vessel, all cavities are tuned in a cleanroom for field flatness >98% and target frequency of 3892.35 MHz. The target frequency for the cavity at 2 K with the blade tuner not engaged is 3899.25 MHz. Alignment requirements are < 0.5 mm for centre of cell deviations. A tuning fixture holds the cavities on the irises and conical flanges and deforms cells individually in axial direction. Cells are stretched along axes to tune frequency up and compressed along axes to tune frequency down. The tuning fixture also allows improving the alignment of the cavity.

Magnetic Shield Design

The specification calls for the magnetic field not to exceed an average of 15 mG across the cavities in the cryomodule. Due to their smaller size, compared to the 1.3 GHz cavities, and the presence of the blade tuner in the middle of the helium vessel, a single magnetic shield on the outside is not feasible. Therefore a hybrid approach with an inner magnetic shield inside the helium vessel and outer endcaps covering the beampipes and the chimney has been designed. Fig. 1 illustrates a 3D CAD cross-section of the cavity with the magnetic shields. The endcaps are shown in blue, covering the beampipes on both sides of the cavity and the chimney. The inner shielding is shown in green, surrounding the cavity itself. It is equipped with small holes all around to allow flow of the liquid helium and three bigger holes located next to the chimney.

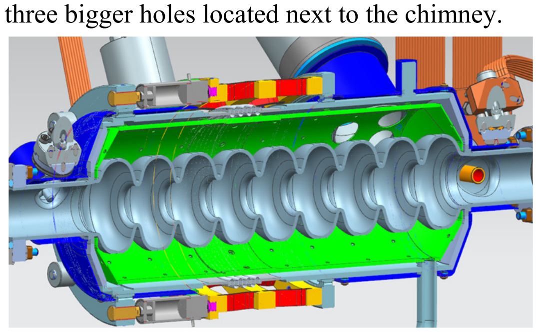

Figure 1: 3D CAD cross-section of a cavity with helium vessel.

VTS TESTS RESULTS

After surface processing, the cavities were equipped with field pickup antenna, HOM coupler feedthroughs and an input antenna, and tested in the vertical cryostat (VTS). To date three cavities (3HRI01, 3HRI02 and 3HRI03) have been tested. The test of 3HRI04 is imminent.

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The VTS test results are shown in Fig. 2. For cavity 3HRI02 and 3HRI03 one test before and after 120°C baking is shown. For 3HRI01 only a test result after baking is available. All tested cavities surpass the specification of a quality factor $Q_0 = 2{\cdot}10^9$ at 13.4 MV/m. For the pre-120°C tests the cavity average Q_0 is $3.5{\cdot}10^9$, while the post-bake tests average is at a higher Q_0 of $4.5{\cdot}10^9$. The maximum accelerating gradient was limited by quench in all cases, between 18 MV/m and 20 MV/m, except for 3HRI01 that reached 25 MV/m.

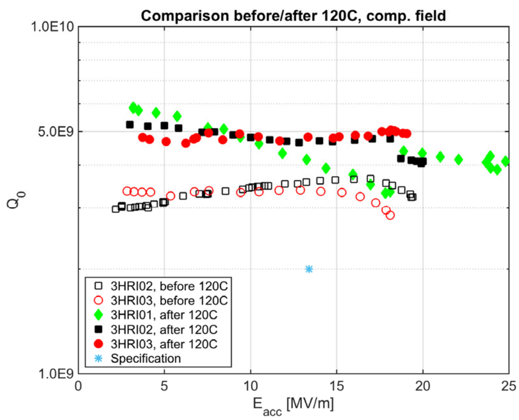

Figure 2: Q vs E performance in VTS, comparison of measurement before and after 120 C baking, cooldown in compensated magnetic field.

Based on these results it was decided to incorporate the 48-hour 120°C baking step for the production cavities.

CAVITY TEST IN HTS

Test Configuration and Diagnostics

To monitor the magnetic field that the cavity is exposed to during the test, the cavity was equipped with four fluxgate sensors. Two were installed before helium vessel welding and sit directly on the cavity itself. One is located on top of cell 1 and is oriented to measure the component of the magnetic field transverse to the cavity beam axis, and the other is on the bottom of the cavity between cells 1 and 2 and oriented to measure the axial component of the magnetic field. Two more fluxgate sensors, oriented for measuring the longitudinal component, are located on the beampipes, one on the input coupler side of the cavity, and the other one on the side with the pickup probe.

Temperature sensors are located on the top and bottom of the cavity helium vessel and the beampipes adjacent to the cavity.

Maximum Gradient and Radiation

During the cavity test in HTS possible radiation originating from field emission in the cavity is monitored by "Chipmunk" detectors. Two detectors are located on the outside of the cryostat aligned with the beam axis of the cavity.

When raising the gradient beyond 15 MV/m, radiation above the background level was measured as shown in Fig. 3. The radiation level rises more or less exponentially as expected, from initial onset at 1 mRrem/hr to $6.3{\times}10^2$ mRem/hr just below the maximum gradient of 20.4 MV/m that is limited by quench of the cavity.

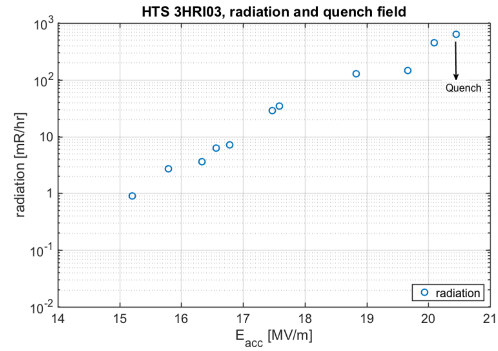

Figure 3: Radiation and quench field of 3HRI03 in HTS.

Magnetic Shield Performance

Figure 4 shows the variation of the magnetic field as measured by the fluxgate sensors on the cavity during its cool down from room temperature to 2 K. After thermalizing at 2 K for a few hours and the thermal currents dying down, the internal fluxgate sensors read less than 0.5 mG in axial and less than 1.5 mG in transversal direction. These fields comfortably meet the specifications.

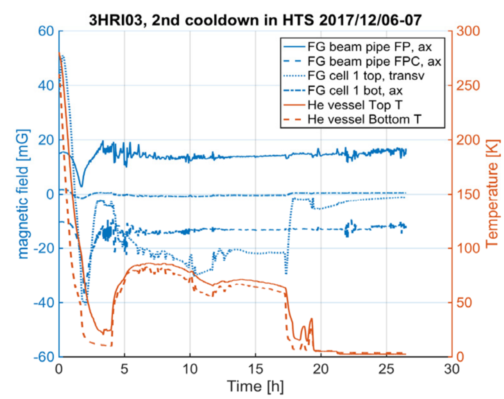

Figure 4: Magnetic fields measured by fluxgate sensors during cooldown.

Chimney Heat Load Limit

One of the major changes in the design of the helium vessel compared to previous versions is the larger diameter chimney. This is necessary due to the higher expected heat loads during cw operation compared to previous pulsed applications. For the maximum operation parameters of Q0 = $1.5{\cdot}10^9$ at 14.9 MV/m, the expected dynamic heat load is 23.6 W.

Since the space on the surface of the helium vessel is limited, the base of the chimney was kept the same diameter, with a step transition to a wider diameter further up, as shown in Fig. 5. The calculated maximum heat load capacity of 36.2 W in the new design provides a 50% margin over the maximum requirements.

The cavity does not generate a large enough dynamic heat load by itself to get close to the chimney heat load limit. Therefore, the cavity was operated at the same time

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as a heater that is fixed to the outside of the helium vessel in order to raise the combined heat load beyond the heat load capacity of the chimney. The cavity was operated at 16 MV/m for this test, corresponding to a dynamic heat load of approximately 12 W. The heater power was raised in steps. With 28 W from the heater, the cavity quenched. This yields a total dynamic heat load of about 40 W, consistent with the heat load calculated from the helium mass flow measured right before the cavity quenched.

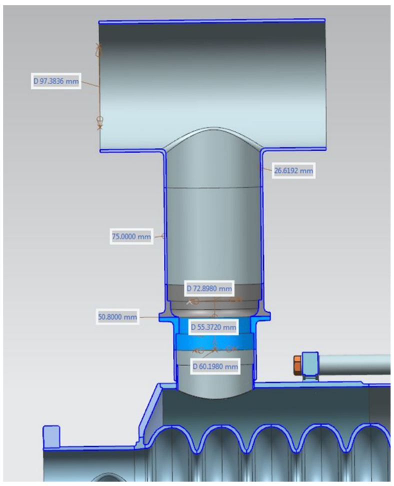

Figure 5: Cross-section through the chimney on the helium vessel.

Cavity Quality Factor

At VTS, the quality factor is determined from pure RF measurements and at HTS it is extracted from heat load measurements. The change in helium mass flow representing the dynamic heat load from the cavity is measured and compared to that of a heater of known power located in the liquid level can.

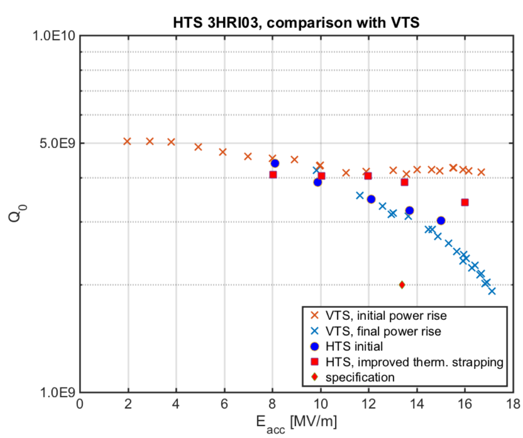

Figure 6: Comparison of Q vs E between VTS and HTS

Figure 6 shows the comparison of the Q vs E curves of 3HRI03 in VTS and HTS. For VTS two curves are shown, the initial power rise and the final power rise, recorded after a field emitter activated, resulting in lower Q. The two Q vs E curves for HTS represent the initial measurement and second measurement after the thermal strapping of the power coupler was improved, resulting in less heating at higher gradients and less heat introduced that made the Q_0 appear lower than actual in the first run.

At 13.4 MV/m the Q_0 is close to $4{\cdot}10^9$, twice as high as the specification of $2{\cdot}10^9$.

OTHER 3.9 GHz SUB-SYSTEMS

The design of the 3.9 GHz fundamental power coupler and performance of the coupler at maximum power of 1 kW cw is presented in [3,4]. The temperature regime of the coupler lies in an acceptable range, but the loaded Q was observed to drift from $1.7{\cdot}10^7$ to $\sim 1{\cdot}10^7$ over the ~2 hours during the coupler heating at maximum power. To fix this unwanted drift we changed the material of the coupler antenna from copper-coated stainless steel to OFHC copper for the production couplers.

Details of frequency tuner design and test results in warm and in cold conditions (in HTS with cavity) is presented in [5]. After eliminating interference with magnetic shielding, the tuner demonstrated all LCLS-II specification for slow tuning with step motor as well as for fast tuning by the piezo-tuner part.

CONCLUSION

The design of all components for the 3.9 GHz cryomodules is complete. We built prototypes and tested them individually, and after all components were assembled on the dressed cavity as an integrated test in the horizontal cryostat. Test results have demonstrated that the cavity and components' performances are close to or exceed LCLS-II requirements for the 3.9 GHz system. The microphonics level is still above specification, but HTS has a very noisy environment. Based on these results Fermilab has started the major procurements for the production cryomodules.

ACKNOWLEDGMENTS

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